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DeRisk — Accurate prediction of ULS wave loads. Outlook and first results

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Abstract

Loads from extreme waves can be dimensioning for the substructures of offshore wind turbines. The DeRisk project (2015-2019) aims at an improved load evaluation procedure for extreme waves through application of advanced wave models, laboratory tests of load effects, development of hydrodynamic load models, aero-elastic response calculations and statistical analysis. This first paper from the project outlines the content and philosophy behind DeRisk. Next, the first results from laboratory tests with irregular waves are presented, including results for 2D and 3D focused wave groups. The results of focused wave group tests and a 6-hour (full scale duration) test are reproduced numerically by re-application of the wave paddle signal in a fully nonlinear potential flow wave model. A good match for the free surface elevation and associated exceedance probability curve is obtained. Finally, the utilization of DeRisk's results in practical design is discussed.

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1. Introduction

The substructures and foundations for offshore wind turbines make up a substantial part of the initial investment. An accurate prediction of the dimensioning loads therefore has a direct impact on the cost of energy. Extreme waves and the associated ULS (Ultimate Limit State) loads can be dimensioning for the diameter and thus the amount of steel needed. The standard procedure for extreme wave design is based on the regular stream function wave theory, see e.g. [1], usually embedded into a linear representation of the background irregular wave climate. This method has gained popularity due to its simplicity in implementation, fast evaluation and limited complexity in input parameters. The associated wave kinematics are fully nonlinear and thus valid all way up to the free surface. By assuming a small diameter to wave length ratio, the Morison equation can readily be applied to determine the associated loads.

The method, however, has a number of limitations due to the assumptions of 2D wave motion, flat bed, periodicity and symmetry around the crest. A constant shape of the wave is assumed. This can lead to notable discrepancies to a real extreme wave which is a transient event in a stochastic sea and thus not likely to have constant form. Also, the assumption of 2D wave motion may not be realistic. At the same time, the constant growth of the wind turbine rotors and the noise-related limitation of the maximum blade tip speed, leads to a constant decrease of the 3P (blade passing) frequency. This in turn forces the natural frequency of the tower closer to the frequency range of wave energy and thus makes accurate wave load prediction more important for large wind turbines.

Advances in numerical wave hydrodynamics during the last two decades have provided new possibilities for a more accurate description of extreme waves and their loads. In the context of the Danish Wave Loads project [2] the fully nonlinear wave model OceanWave3D of Engsig-Karup et al.[3] was applied to loads on monopiles [4–6]. Further, building on previous work at DHI and DTU [7–9], a coupled solver that utilises OceanWave3D to drive a local CFD solver around the substructure was developed by Paulsen et al.[10], enabling computation of fully nonlinear 3D irregular wave loads, even for breaking waves.

While these tools and methods have been demonstrated to work well, the lift into today's design practice is still missing. This next step, needs further systematic model validation and detailed considerations of today's design approach. While new methods for design and load calculation can be introduced in many ways, a full value impact into today's design procedure requires a well thought out path for their application and careful consideration of the existing design methods.

These tasks are the focus of the Danish DeRisk project (2015–2019). The project involves 9 partners and covers development of efficient wave models, physical model tests, development and validation of load models, dynamic response modelling and incorporation of the methods into a new load evaluation procedure. The present paper is the first from the project and outlines the research content of DeRisk and its expected results. Sample results from the first series of physical model tests and their numerical reproduction are presented. Finally the practical utilization of the project results is discussed.

2. Elements of DeRisk

DeRisk runs from 2015 to 2019 with participation of DTU Wind Energy, DTU Mechanical Engineering, DTU Compute, DHI, University of Oxford, University of Stavanger, DONG Energy, Statkraft and Statoil. The aim of DeRisk is to provide a de-risked load evaluation procedure for ULS wave loads on offshore wind turbine substructures. The project ambition is to combine physical model tests and advanced numerical models to gain understanding and insight into the physics and statistics of the hydrodynamic forces and associated loads. Next, the results are utilized to device practical engineering methods that build on a subset of the models and parameterized results. The project work is focused around five main elements, as detailed below.

2.1. Efficient wave models

Wave transformation from deep to intermediate and shallow water is a nonlinear process. Especially for storm waves, the nonlinear effects are important and lead to deviations between the spectra and free surface elevation time histories at the relevant depth and those that are associated with the standard spectra such as JONSWAP or Pierson-

Moscowitz. Also, for force computation of ULS events, reliable kinematics that are valid all the way up to the free surface are needed.

Both needs can be accommodated by the use of fully nonlinear wave models. Building on a long tradition at DTU for development of nonlinear wave models e.g. [11], DeRisk applies the OceanWave3D model of Engsig-Karup et al.[3]. This model solves the 3D Laplace equation over varying depth and with fully nonlinear free surface conditions. It has been used in the Wave Loads project to study the effect of wave nonlinearity on life-time fatigue of monopiles [5,6] and jacket structures [12]. OceanWave3D has further been implemented at GPU architecture, allowing massively parallel computation of large wave fields [13]. As part of DeRisk, the GPU model is extended to 3D wave generation that also allows direct reproduction of laboratory tests with wave paddles and an improved breaking model which is calibrated against measurements. Once validated against laboratory test results, the GPU enabled wave model will be utilized to compute statistics of large 3D wave fields and fully nonlinear kinematics for force and response calculations on wind turbine structures. To ease the practical application, a kinematics data base will be produced and made freely available. Hereby, fully nonlinear kinematics will be readily accessible for practical use without explicit new wave model calculations.

2.2. Wave physics

A thorough understanding of the physics behind the loads is vital for a meaningful approach to its modelling and parameterization into design. For this reason, detailed experiments are carried out in 3D (DHI) and 2D (DTU) environments. The physical effects directly addressed are 3D wave spreading, the effect of wave-current interaction, the effect of enhanced bottom slope in the lab and the effect of air-entrainment from wave breaking. PIV measurements of incident wave kinematics are made to allow direct validation against numerical kinematics and to enable validation of force models based on the incident kinematics. While many of the mentioned effects are already known and described to a certain level, the focus of the investigations are on the associated impact on the hydrodynamic loads. The purpose of the tests are two-fold. The tests must document the load effects in their own right, and further allow validation of the numerical models which can then later be used to extend the parameter space. We aim at a level of accuracy that allows uncertainty reduction and thus enables more accurate load predictions. Following the work of Bigoni et al.[14,15], mathematical and numerical methods for uncertainty quantification are applied to quantify the uncertainties of the model output.

2.3. Hydrodynamic load models

Hydrodynamic load modelling is the discipline of transforming incident wave kinematics to structural loads. The Morison equation and Rainey force models [16,17] provide a simple means for slender bodies and are often surprisingly accurate. For linear waves, the MacCamy-Fuchs theory provide the necessary diffraction correction which for shorter waves lead to significant load reductions. Detailed wave-structure interaction can be computed by CFD methods. In the Wave Loads project ringing loads from highly nonlinear regular waves were studied with the OpenFOAM solver [18]. Further Paulsen et al.[10] developed a coupled OceanWave3D–OpenFOAM solver that enabled even 3D irregular wave impacts to be modelled by driving a small CFD domain by kinematics of a larger OceanWave3D domain.

Continued development is undertaken in DeRisk to achieve a force model that allows fully nonlinear kinematics and diffraction at the same time and includes an improved description of loads associated with wave breaking. A correct description of the vertical variation of the load profile is important, as this has a direct impact on the dynamic response of the structure. Again, the experimental results will be utilized to validate the force and impact models. CFD can also be used in this context. Further, the well-known topic of ringing and the secondary load cycle which is observed as a small additional force peak following the main force peak of a large wave event will be investigated in detail. While the regular wave study of [10] showed good comparison to lab measurements, the role of the structural boundary layer still needs to be clarified. This is also relevant for wave impacts where the drag-load component becomes large. A CFD strategy for steep wave impacts with inclusion of the boundary layer effects will therefore be developed.

2.4. Response of the full offshore wind turbine structure

Engineering design of offshore wind turbine structures is based on aero-elastic response computations for a number of load cases, typically of 10-minute length. The design loads are derived from the structural stresses and are thus associated with the dynamics of the full structure and not just the external hydrodynamic loading. Load effects of importance here are thus the wind loads, exerted by the rotor; the associated aerodynamic damping and the damping effect of soil. Depending on the actual site conditions, the design driving load cases can thus be load cases of wave-only forcing as well as load cases of combined wind and wave forcing. A specific case to study is the implications of steep nonlinear waves during a 36 hour storm and the potentially increased risk of permanent tower-soil skew settling. These effects are dealt with through aero-elastic computations with the Flex5 [19] and HAWC2 [20] models. Response characteristics of jacket structures are dealt with too. Here, the WaveSlam data set [21] is analyzed and used to validate load and response models for jacket structures. The recent work at University of Oxford and Singapore on the current-blockage effect for wave loads on jackets [22,23] is extended and applied to quantify the associated load reduction for wind turbine jacket structures. Finally, full-scale data from an offshore monopile wind farm is analysed for extreme wave impacts and ringing-effects. The intention is to gain insight into the frequency of occurrence of ringing events and events of impulsive excitation by steep and breaking waves.

2.5. De-risked design

Practical use of the project results requires a firm knowledge of the existing design procedure and a focused documentation of the consequence of applying the new techniques. Also the cut between application of the (perhaps) heavier new numerical models and parameterized/pre-computed results is important. To this end, the results and methods developed are collected into the desired de-risked load evaluation procedure for extreme waves. This includes the statistical combination of short-term environmental parameters into the 50-year state with reduced uncertainty, and joint-probability analysis that includes structural response.

Also, proper benchmarking to quantify the effect of application of the new techniques on realistic design cases is needed. In DeRisk, this is achieved by producing a white paper on the present design chain and its uncertainties. A set of benchmark cases is defined, to allow transparent benchmarking of the tools and methods against the existing design procedure.

3. First results

The 3D experiments were carried out in the shallow water basin at DHI in November–December 2015. The aim of the experimental campaign was two-fold: to establish experimentally based probabilistic information on crest-elevation and force statistics for ULS wave climates typical for wind farm locations in the North Sea; and to provide data for validation of the numerical models. Although storm events are typically represented by 3-hour realizations of a wave climate, the tests were made with a duration of 72 hours (full scale time) to reduce the stochastic scatter for the probability level corresponding to 3 hours. The tests were mainly carried out with directionally spread waves to best replicate realistic wave conditions and to provide information on the effect on the crest elevation and force statistics. Additional shorter (6 hour) reference tests of 2D climates were carried out to allow a direct analysis of the spreading effect. The experiments were carried out in scale 1:50 with full scale depths of 20 m and 33 m. The monopile diameter was 7 m which is larger than the typical monopile diameter of 6-6.5 m of today's wind farms. An additional thin cylinder of 1.5 m diameter (full scale), the 'drag column', was placed in the basin to provide force measurements for a drag-dominated structure of dimensions similar to a jacket leg for offshore wind turbine use.

A sketch of the experimental setup is shown in figure 1. Absorbing rock berms were placed around the setup to avoid reflections to the largest possible extent.

Tests for focused wave groups were included as well for each of the wave climates tested. The focused wave group theory, or New Wave Theory, originates from Lindgren[24], Boccotti[25] and Tromans et al.[26] and describes the expected time history of an extreme wave crest for a given wave climate. The theorys central result is that this time history of the extreme event is simply the auto-correlation of the wave spectrum itself, which for a discretized

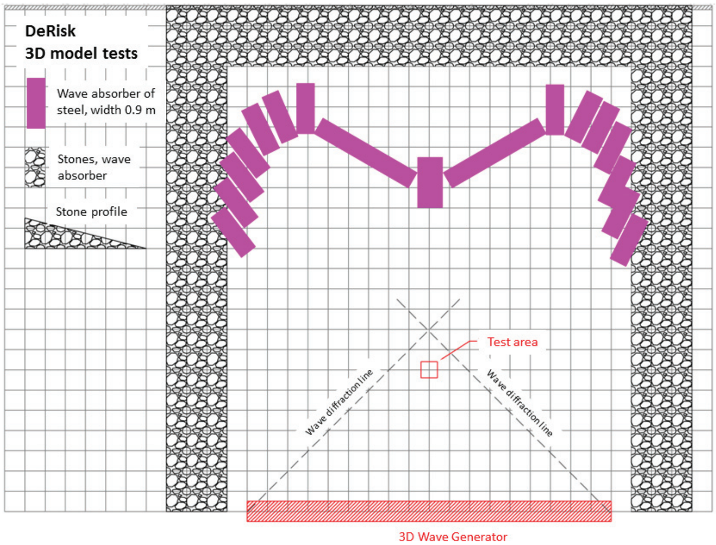

Fig. 1. Experimental setup for the 3D wave tests at DHI.

spectrum reads

$$\eta(x,t) = \frac{\alpha}{\sigma^2} \sum_{j=1}^{N} S_\eta(f_j) \cos\Big(\omega_j(t-t_0) - k_j(x-x_0)\Big)\,\Delta f \tag{1}$$

where S_η is the wave spectrum, σ^2 the variance of the free surface elevation and α the crest-height of the extreme wave. For the present tests, α was chosen such that the height of the focused wave (1) was 1.86 times the significant wave height of the wave climate, in agreement with a Rayleigh distribution of wave height at the 3-hour probability level.

For the directionally spread wave climates, the focused waves were established by the 'double summation method', where the directional spectrum is discretized into a number of directions:

$$\eta(x,t) = \frac{\alpha}{\sigma^2} \sum_{j=1}^{N_{\text{freq}}} \sum_{l=1}^{N_{\text{dir}}} S_\eta(f_j,\theta_l) \cos\Big(\omega_j(t-t_0) - k_{x,jl}(x-x_0) - k_{y,jl}(y-y_0)\Big)\,\Delta f. \tag{2}$$

Here $(k_{x,jl}, k_{y,jl}) = k_j(\cos\theta_j, \sin\theta_l)$. While this method yields the desired lateral symmetry of the extreme wave event, it has the disadvantage of a spatially varying significant wave height in the basin. Thus for the stochastic realizations, the 'single summation method' was used, where at each frequency, the wave direction is chosen randomly from a given directional distribution. The nonlinear evolution and scaling of directionally spread waves at deep water have been analysed by Adcock et al.[27].

3.1. 2D and 3D focused waves — Free surface elevation

Figure 2(a) shows the free surface elevation for a 2D focused wave, generated for a JONSWAP wave climate of $H_s = 9.5$ m, $T_p = 12$ s and $\gamma = 3.6$. The blue curve is the experimental free surface elevation, measured at the same distance from the wave maker as the monopile but displaced 0.2 m (lab) in the lateral direction. It shows the expected build-up of a wave signal towards a large wave of 0.18 m (lab) crest amplitude. The first and second troughs before the main crest show a spurious additional crest. These are the result of scattered waves from the pile. Towards the end

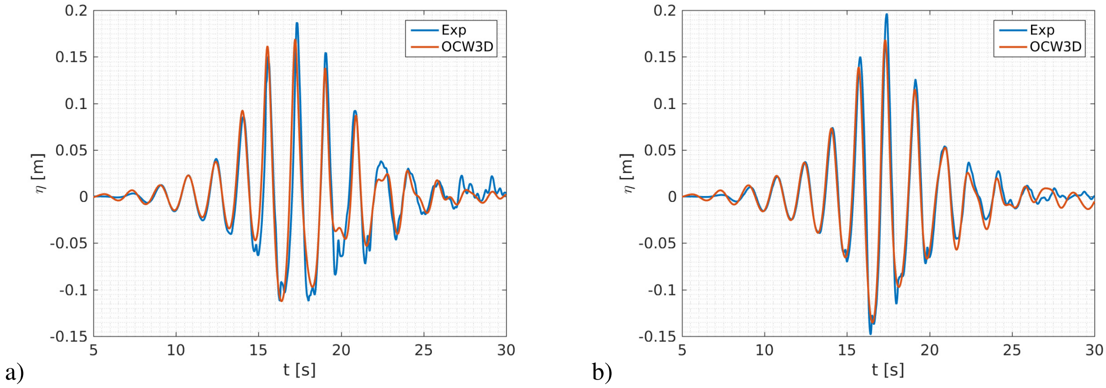

Fig. 2. Free surface elevation for focused wave group tests. (a): 2D focused wave group. (b): 3D focused wave group.

of the wave group, around $t = 22$ s (lab), short-wave phenomena are visible in the signal. These may be caused by spurious second-order waves in the basin due to the first-order wave generation technique and reflections.

The numerically reproduced signal is shown in the same plot by a red line. The numerical domain replicated the physical domain and waves were generated by application of a volume flux signal equal to the specified velocity of the physical piston wave makers. Overall there is a good agreement and similar to the experimental signal, short-wave components are visible after the main wave group. Some differences between the measured and computed crest-heights for the three largest waves can be seen. Inspection of video recordings from the experiment, however, shows that the main waves of the group were breaking on the way towards impact. The deviations can thus be linked to the approximate breaking filter of the model. In general also the trough elevations are matched fairly well, perhaps with a tendency of slightly reduced trough depth. It is noted that the numerical signal does not show the extra crests inside the troughs, since the computation is only 2D and does not include the structure and associated scattered waves.

Results for the corresponding 3D focused group is shown in figure 2(b). Compared to the 2D group, the focusing up to the largest amplitude is more localized in time, leading to a more narrow group envelope. This is due to the directional focusing effect, where the large wave crests are partially built up by waves of different directions 'meeting up' at the focus location, whereas for the 2D group, all focusing must occur due to differences in phase speed only. This effect and the associated impact on the force statistics of large wave climates is one of the DeRisk focus areas. The numerical reproduction of the group is of good quality with deviations only for the three main crests. For this test, the trough elevations are matched perfectly, although with no reproduction of the scattered waves, which occur in the experimental signal due to the structure.

High-speed video of the focused wave group tests and selected events of the long time series realizations were obtained as part of the campaign. A snapshot of the 3D focused wave of figure 2 is shown in figure 3 along with a picture of the undisturbed free surface of the OceanWave3D reproduction. Note that for the numerical figure, the monopile has only been inserted for visual purposes, as the computation does not include the structure. A good visual comparison between the physical test and numerical reproduction is seen, consistent with the good match in figure 2. Detailed computations of wave-structure interaction will be made during the project following the work of Paulsen et al.[10].

3.2. Stochastic waves in 2D

While the focused wave group results provide generic events that are readily replicated numerically due to their isolated appearance in time and space, the Engineering interest for offshore structures is in the force statistics. This is the motivation for the long experimental time series which on their own provide statistical information for the parameters tested, and which upon successful reproduction within the numerical models can be extrapolated to other parameter values numerically. As one example of this process, figure 4 shows the exceedance probability curve for crest heights from a 2D test with same wave spectrum as the 2D focused wave of figure 2(a). The full scale duration of

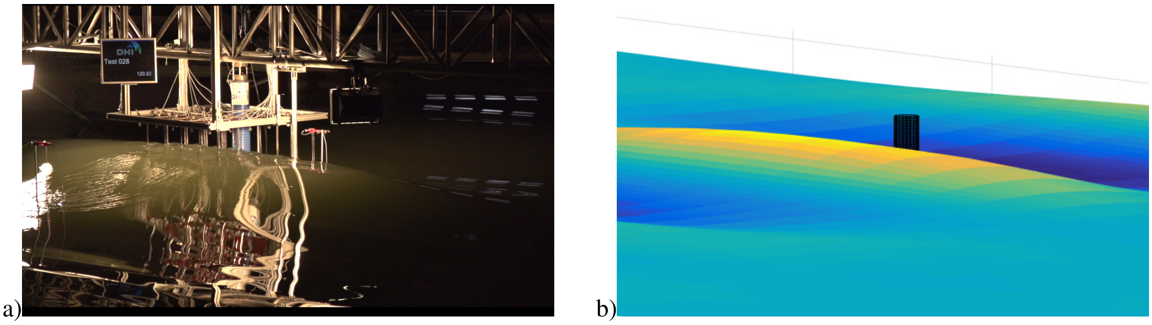

Fig. 3. (a) High-speed snapshot of 3D focused wave impact. (b) Numerical reproduction of incident wave field.

the test is 6 hours. The probability level for the largest crest of a 3-hour storm is thus equal to the level of the second-largest data point which has a measured crest height of 0.2 m (lab scale). This is slightly more than the focused wave group with a crest height of 0.18 m. In later analysis, the focused wave group and events of the stochastic time series results will be compared in detail.

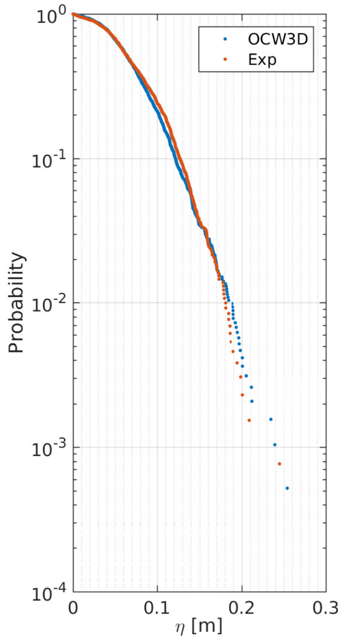

Fig. 4. Exceedance probability curve for crest-elevations for a 6-hour realization of a 2D wave climate.

The 6-hour (full scale duration) time series was reproduced in OceanWave3D by application of the same wave paddle signal as for the test. The crest height probability curve is plotted on top of the experimental results in figure 4. A good match is seen for exceedance probabilities between 100% and about 40%. For larger crest heights, some underprediction is seen, while again for crest heights between 0.14 m and 0.17 m (lab scale) good agreement is obtained. Finally for the largest crests, the model overpredicts the crest heights. This is thought to be caused by wave breaking in the experiment — either during wave generation or during the transformation to the structure. For the present computations, wave breaking is only represented by a simple filter on the vertical particle acceleration of the waves and local removal of energy. A well-calibrated breaking model is part of the DeRisk research and will be utilized with the aim of obtaining a close match between the model and test results.

4. Discussion

The loads from extreme waves are in some cases dimensioning for the substructure of offshore wind turbines. In this paper, the collaborative research project DeRisk (www.derisk.dk) with the aim of providing a de-risked load evaluation procedure for the extreme wave loads, has been described . The research builds on numerical tools, physical model tests and statistical analysis. A central philosophy in DeRisk is the validation of numerical models against laboratory tests and next extrapolation of the physical test results to the full parameter space. Hereby, detailed investigations with the validated models can be made. Another important part of the project is the split between model application and parametrization for engineering use. A proper balance is important for the applicability in practical design.

DeRisk will hereby provide results of both a physical, scientific and practical nature. Through detailed benchmarking of the new tools against realistic benchmark cases, the new methods will be assessed against the existing design methods. It is the project ambition that its results can enter into practical design and design codes. To this end the fully nonlinear kinematics data base, the new force model and the parameterized physical effects are expected to be especially valuable. Hereby DeRisk will enable application of fully nonlinear kinematics for the design of offshore wind turbine structures.

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